

# An Auto-tuning Controller for Networked Control Systems

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**Abstract**—In this paper, we introduce a proportional-integral-derivative (PID) auto-tuning controller by using relay feedback and online gain updating method for networked control systems (NCSs). The proposed controller takes both advantages of relay feedback, which provides the initial knowledge of the control system, and updating method, that adapts to the changing input and load disturbance. In order to validate the effectiveness of our design, the proposed controller is evaluated experimentally with cFP 2220 platform from National Instruments, and with LabVIEW programming software. The results show that our design obtains superior tracking performance.

**Keywords**— networked control system; PID auto-tuning; relay feedback; changing input and load disturbance; LabVIEW

## I. INTRODUCTION

Network control systems (NCSs) research, which includes three different research areas: control system, communication networks and information theory, and computer science [1], has attracted considerable attention in recent years. NCSs offer various advantages such as cost-effectiveness of installation to design large-scale systems, flexibility in implementation, reliability, and the ease of maintenance [2], as well as widespread applications. However, there are significant challenges arising for control design, since the system usually no longer follows the rules of classical control theory. The main problems are varying time delays due to communication and computation, and packet losses [3].

Regarding controller design, despite the growing interest towards more advanced control algorithms, the PID controllers still have a dominant status in practice because of its low cost, simplicity in terms of less numbers of parameters to be tuned and applicability on a wide range of operating conditions [4]. Nevertheless, using PID controllers in NCSs has not been thoroughly investigated, especially with regard to controller's parameters tuning to achieve robustness against the challenges of NCSs [5]. On the practical implementation of a PID controller, there is a possibility that, because of human intervention, the process is not tuned to obtain optimum control. Hence auto-tune method serves a vital role as it automatically tunes the parameters and controls the process to its optimum limits. Among many advanced PID auto-tuning approaches, such as fuzzy logic, neural network, or genetic [6],

relay feedback method introduced by Astrom and Hagglund [7] is still used widely in practice. This approach requires minimal amount of priori information and less sensitive to modelling errors and disturbances compare with other methods.

In this work, we propose a PID auto-tuning controller by combining relay feedback, introduced by Astrom and Hagglund, and online gain updating method [8] in order to deal with the changing desired input and load disturbance problems in NCSs. By considering the specifications of the networked control system structures, effects of different conditions on relay feedback test and different scaling values in the updating method, a hardware system is designed and software is developed to implement and validate the present work.

The rest of the paper is organized as follows: Section II describes specifications of different control system structures that can be used to construct NCSs. Section III presents our main results: the design of PID auto-tuning controller by using relay feedback test and online gain updating method. The designed hardware, developed software, and experimental results are given in section IV. Finally, section V derives conclusions.

## II. CONTROL STRUCTURES

In a NCS, there are three possible designs of control structure, which have the network existed in three different places in the system, namely, control structure with the operator located remotely, control structure with the controller located remotely, and control structure with bilateral controllers [9]. These structures (see figure 1, 2, 3) have different specifications, relating to the problems of NCSs, which are highlighted as follows

### A. Structure with the operator located remotely

In this structure (see fig. 1), control commands and desired inputs are remotely sent to the controller via communication network. Because the network is excluded from the closed loop and the controller is located at the same location as plant, the network-induced delays and packet losses will not affect the performance of the control system. However, these problems will affect the transfer of the desired inputs from the operator as well as the measured outputs, which can be compensated by measurements. As a result, if we want to reduce the effect of

the problems when designing a NCS, the structure with operator located remotely is a good solution.

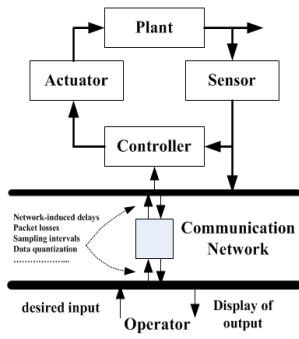


Fig. 1. Control structure with the operator located remotely

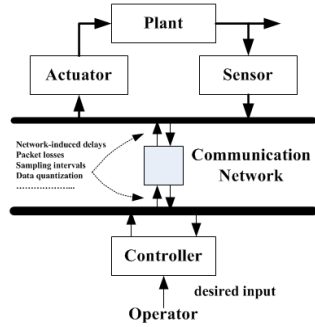


Fig. 2. Control structure with the controller located remotely

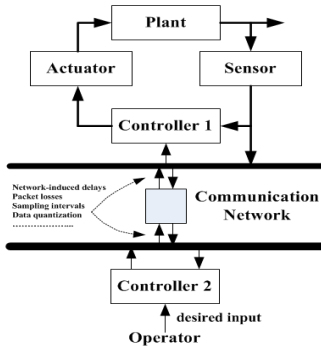


Fig. 3. Control structure with bilateral controllers

### B. Structure with the controller located remotely

In this case (see fig. 2), the controller is located at the remote site. The communication network has become part of the control system, in other words, in both the communication channels, actuator and sensor, the delays and packet losses are introduced. These problems will significantly influence the performance and stability of the control system. Beside the developing appropriate control theories and approaches, improving the communication infrastructure can limit the effect of those problems, for example, using real-time network with high bandwidth Ethernet and suitable network protocol

[10]. In practice, controllers, such as Programmable Logic Controller (PLC) or Fieldpoint Real-Time Controller, which provide real-time Ethernet communication, can use directly in this structure with minor imperfections.

### C. Structure with bilateral controllers

With bilateral control structure, which has one controller located on the plant site, another on the operative site, and linked through the network (see fig. 3), the advanced control algorithms with multiple functionalities can be deployed directly. Usually, while the controller at the plant site would be responsible for regulating during normal operation, the controller at the operator site can be used to tune the parameters and/or change the desired input of its counterpart when conditions or situations changed.

By considering all possible structures above, it is important to note that with an appropriate control structure, the problems of NCSs partly can be overcome. Furthermore, the structures provide a flexibility in designing software for control systems, for instance, producer-consumers or server-clients architectures can be realized easily.

## III. DESIGN OF PID AUTO-TUNING CONTROLLER BASED ON RELAY FEEDBACK AND UPDATING METHOD

The proposed PID auto-tuning controller, using updating method based on the relay feedback approach, control structure is shown in Figure 4. The controller is designed as follows.

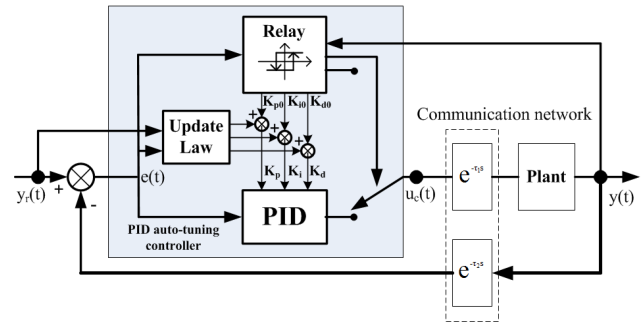


Fig. 4. Control system with the proposed PID auto-tuning controller

Firstly, the relay feedback control is carried out to analyze the system dynamic and calculate the ultimate gain and ultimate frequency by the peak detection and the number of zero crossing times. Then, by using the closed-loop method of Ziegler-Nichols, the initial parameters of PID controller are given. Secondly, in PID control mode, with the update law proposed by A. K. Sukede, J. Arora [8], the PID gains are tuned automatically. Whether we consider the network part depends on which control structure uses.

### A. Relay feedback control

The method actually determines the gain,  $a$ , introduces capable of introducing a phase lag of  $\pi$  when operating in feedback under the ultimate period,  $P_u$  (see fig. 5). This is the critical gain. The ideal relay feedback control is carried out by:

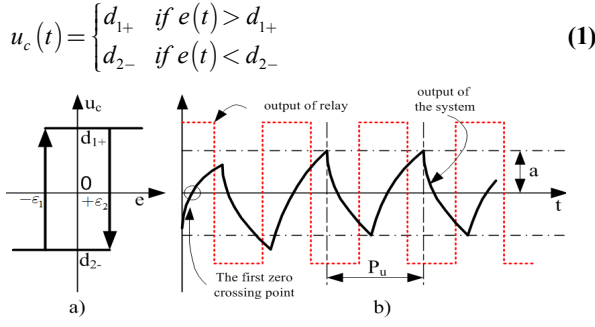


Fig. 5. Relay, control signal, and the output of the system

Where,  $u_c(t)$  is the control input,  $d_{1+}$ ,  $d_{2-}$  ( $|d_{1+}| = |d_{2-}| = d$ ) are the levels at which the control signal switch to the opposite site (here, hysteresis:  $|\varepsilon_1| = |\varepsilon_2| = 0$ ), and  $e(t)$  is the error of the control system ( $e(t) = y_r(t) - y(t)$ ).

Apply the relay feedback control to a system, we receive a periodic signal with amplitude,  $a$ , and period,  $P_u$  (fig. 5) at the output of the system. As a result, the ultimate gain,  $K_u$ , and ultimate frequency,  $\omega_u$ , can be calculated as follows [11]:

$$\begin{cases} K_u = \frac{4d}{\pi a} \\ \omega_u = \frac{2\pi}{P_u} \end{cases} \quad (2)$$

In addition, the authors also pointed out that, with different operating conditions, different types of available relays should be chosen, for instance, dealing with the load disturbance or non-linearity of the control system, the relay would have:  $|d_{1+}| > |d_{2-}|$ . Furthermore, Marco Goncalo de Sousa Neves [12] showed that the introduction of hysteresis ( $|\varepsilon_1| \neq 0 \neq |\varepsilon_2|$ ) in the relay method clearly improves the estimation, reducing the sensitivity of noise and disturbance.

### B. PID auto-tuning controller with updating method based on relay feedback

The discrete form of PID controller can be represented as follows

$$u_c(k) = K_p e(k) + K_i \sum_{i=1}^k e(i) \Delta t + K_d \left[ \frac{e(k) - e(k-1)}{\Delta t} \right] \quad (3)$$

Where  $u_c(k)$  is the control output,  $\Delta t$  is the sampling time,  $K_p$  is the proportional gain,  $K_i$  is the integral gain,  $K_d$  is the derivative gain, and  $e(k) = y_r(k) - y(k)$ , is the error. The PID gains can be calculated as follows

$$\begin{cases} K_p = K_{p0} + \Delta K_p \\ K_i = K_{i0} + \Delta K_i \\ K_d = K_{d0} + \Delta K_d \end{cases} \quad (4)$$

Where,  $K_{p0}$ ,  $K_{i0}$ ,  $K_{d0}$  are the initial PID gains, which are calculated by the closed loop method of Ziegler-Nichols as shown in Table I.

TABLE I. THE ZIEGLER-NICHOLS TABLE

Controllers	Parameters of PID controller		
	$K_{p0}$	$K_{i0}$	$K_{d0}$
P	$0.5 * K_u$		
PI	$0.45 * K_u$	$0.85 * P_u$	
PID	$0.6 * K_u$	$0.5 * P_u$	$0.125 * P_u$

And,  $\Delta K_p$ ,  $\Delta K_i$ ,  $\Delta K_d$  are updating values of PID gains so as to recover quickly the effect of both the set point changes and load disturbance. Those values are calculated as follows [8]:

$$\begin{cases} \Delta K_p = k_{11} |\alpha(k)| \\ \Delta K_i = k_{12} \alpha(k) \\ \Delta K_d = k_{13} |\alpha(k)| \end{cases} \quad (5)$$

Where,  $k_{11}$ ,  $k_{12}$ ,  $k_{13}$  are scaling factors (constants), and  $\alpha(k)$  is updating factor, which is calculated by:

$$\begin{cases} \alpha(k) = e_n(k) * \Delta e_n(k) \\ e_n(k) = \frac{e(k)}{|y_r(k)|} \\ \Delta e_n(k) = e_n(k) - e_n(k-1) \end{cases} \quad (6)$$

Basically, the PID controller with the gains calculated by relay feedback method cannot adapt to the dynamic changes or load disturbance. However, the our proposed PID controller, which takes advantages of both the relay feedback method and updating method given by A. K. Sukede, J. Arora [8], can respond quickly to the dynamic changes or load disturbance.

## IV. CASE STUDY

This section will illustrate the use of the proposed control algorithm in a NCS for tracking velocity of an induction motor. To validate, we set up a NCS which can be portable all structures mentioned in the section II, and develop a software for this system.

### A. Hardware structure for controlling the motor

As shown in Figure. 6, the whole system consists of six key parts: induction motor, Fieldpoint real-time controller from NI (2220) with the ability of networking communication via Ethernet, sensorless vector frequency inverter (VFD-E), encoder, personal computer (PC), and networking devices.

With this platform, we can deploy any control structure examined in section II. For example, when we use control structure with the operator located remotely (fig. 1), the control algorithm will be developed in the real-time controller in order to control the speed of the motor. Nevertheless, the PC is used to provide the desired speed input and monitor control parameters such as motor control signal, the parameters of the controller, and current motor speed.

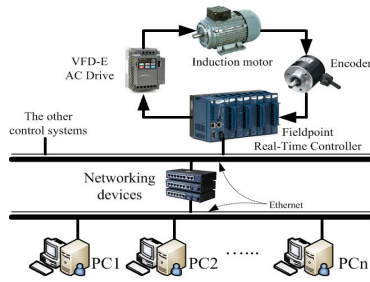


Fig. 6. Hardware structure of the developing NCS

### B. The software design for tracking the speed of the motor

The software of the system is designed by using server-client model (see Figure. 7). While the client is deployed in the PC, the server is run on the real-time controller. As a result, the effect of the network-induced delays can be ignored because the network is not a part of the control loop.

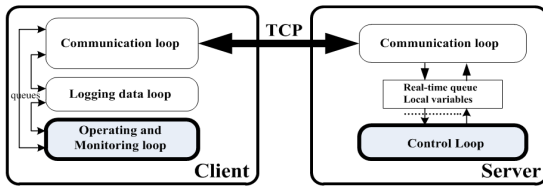


Fig. 7. Software structure for deploying the proposed control algorithm

In this architecture, the software is divided into two parts: the client side and the server side, communicated by TCP protocol. The client side, which has a user interface is shown in Figure. 8, does some functionalities such as operating, monitoring, logging data, and doing communication with the server.

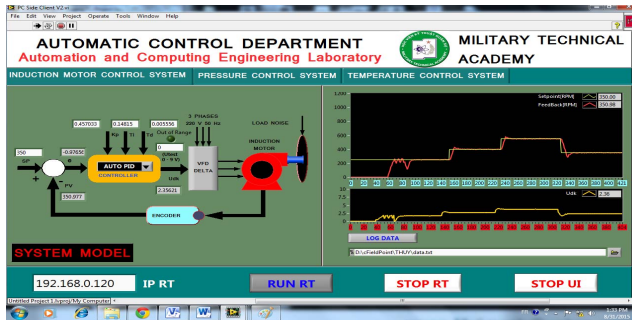


Fig. 8. Tracking speed result of the induction motor in the NCS

In order to implement the above functionalities, a producer-consumer architecture with multithreading programming techniques is used. On the other hand, the main function of the server side that is implementing the proposed control algorithm – PID auto-tuning controller so as to track the desired speed of

users. All programs are developed by using LabVIEW from National Instruments.

### C. Experimental results

In order to illustrate the performance of the our implementation in this paper, the system is tested on the scenario by changing the desired speed of the motor combining with load disturbance. Fig. 8 shows the result of the speed tracking with the proposed PID auto-tuning controller. The output speed follows to the successive set point changes with good performance. It confirms that the proposed PID auto-tuning controller deals with the input changes and load disturbance well.

## V. CONCLUSIONS

This paper introduces a PID auto-tuning controller using updating law proposed by A. K. Sukede, J. Arora based on relay feedback method for NCSs. A careful consideration of the relay settings for different conditions is examined. Then, to verify the effectiveness of the proposed control algorithm, a hardware is designed and a software is developed. The results have shown that the controller can track a wide range of velocity with high robustness, and this controller can be used in many applications in industry.

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